energies

MDPI

Supplementary Materials

Environmental Policy Stringency, Trade Openness, and the Energy Transition: Convergence in Green Patenting, 1990–2020

Luis Lalin-Bermudez, Dely Ramirez, Mario Morel and Karla Fernandez-Norales

This file contains: Table S1 (pairwise correlation matrix of key panel variables), Table S2 (robustness of the lagged EPS coefficient to alternative lag lengths), Table S3 (Revealed Technological Advantage and Y02 share by country, 2010–2020 averages), and Note S1 (data construction and country classification).

Table S1. Pairwise correlation matrix of key panel variables (1240 country–year observations, pairwise-complete observations).

	Y02 share	EPS	Trade openness	log(GDP per capita)	log(Population)	Exports (% GDP)	Imports (% GDP)	Government effectiveness
Y02 share	1.000	0.287	0.051	0.020	0.016	0.051	0.051	0.014
EPS	0.287	1.000	0.351	0.483	−0.093	0.351	0.347	0.366
Trade openness	0.051	0.351	1.000	0.343	−0.616	0.996	0.994	0.272
log(GDP per capita)	0.020	0.483	0.343	1.000	−0.561	0.354	0.326	0.846
log(Population)	0.016	−0.093	−0.616	−0.561	1.000	−0.601	−0.627	−0.543
Exports (% GDP)	0.051	0.351	0.996	0.354	−0.601	1.000	0.981	0.281
Imports (% GDP)	0.051	0.347	0.994	0.326	−0.627	0.981	1.000	0.258
Government effectiveness	0.014	0.366	0.272	0.846	−0.543	0.281	0.258	1.000

Three additional variables used in supplementary robustness checks—exports (% of GDP), imports (% of GDP), and government effectiveness—are also included in the correlation matrix above (N = 1231 for exports and imports; N = 1240 for government effectiveness; pairwise-complete observations). Two patterns are worth noting: exports and imports are each correlated with the existing trade openness measure at 0.99 or higher (expected, since trade openness is their sum) and with each other at 0.98, which limits the extent to which their separate effects can be distinguished; and government effectiveness is correlated with log(GDP per capita) at 0.85, indicating that the governance and income dimensions overlap substantially in this sample.

Table S2. Robustness of the lagged EPS coefficient to alternative lag lengths. Country and year fixed-effects models; dependent variable log(Y02 patents + 1). Country-clustered robust standard errors in parentheses. Trade openness, log(GDP per capita), and log(Population) are included as controls in every model but omitted from the table for brevity (full output available from the corresponding author). The full specification, including these control coefficients, model N, and within R^2, is reported directly below in Table S2 (continued).

Lag of EPS	Coefficient (SE)	t value	p value
1 year	0.075 (0.068)	1.10	0.272
2 years (baseline)	0.105 (0.086)	1.22	0.222
3 years	0.110 (0.086)	1.27	0.203

Table S2. (continued). The coefficients on the control variables omitted from Table S2 above (trade openness, log(GDP per capita), log(Population)), for the same three lag-length specifications of the EPS coefficient, together with model N and within R^2. Estimated in Python (linearmodels PanelOLS, country and year two-way fixed effects, country-clustered standard errors) as an independent cross-check of the original R specification reported in Table S2; this Python implementation reproduces the original EPS-lag coefficients and standard errors in Table S2 to within the small numerical differences ordinarily seen between R's and Python's cluster-robust variance estimators (documented in the R and Python analysis scripts referenced in Note S1). The complete model code and output underlying both tables are available from the corresponding author upon reasonable request, consistent with the manuscript's Data Availability Statement.

Lag of EPS	Trade openness	log(GDP per capita)	log(Population)	N	R^2 (within)
1 year	−0.0010 (0.0026)	1.775 *** (0.420)	0.514 (0.880)	1194	0.278
2 years (baseline)	−0.0009 (0.0028)	1.776 *** (0.429)	0.522 (0.904)	1156	0.275
3 years	−0.0010 (0.0028)	1.765 *** (0.451)	0.518 (0.910)	1118	0.268

*** $p < 0.01$. *Dependent variable log(Y02 patents + 1) in all models, matching Table S2 above.*

Table S3. Revealed Technological Advantage (RTA) in Y02 patenting and Y02 share of total patents by country, 2010–2020 averages, ranked from highest to lowest RTA. RTA above 1 indicates specialization relative to the aggregate Y02 share of the 40 sample countries (the "world" share defined in Section 3.4 of the main manuscript). "Developed" and "Emerging" group assignments match Section 3.1 of the main manuscript.

Country	Group	Average RTA	Average Y02 share (%)
Denmark	Developed	2.13	24.0
Chile	Emerging	1.35	15.2
Korea	Developed	1.26	14.1
France	Developed	1.13	12.8
Spain	Developed	1.12	12.6
Germany	Developed	1.09	12.3
Finland	Developed	1.01	11.4
Japan	Developed	1.01	11.3
Estonia	Emerging	0.99	11.0
Austria	Developed	0.98	11.1
Sweden	Developed	0.98	11.0
United Kingdom	Developed	0.97	10.9
Slovak Republic	Emerging	0.94	10.5
United States	Developed	0.93	10.4
Russia	Emerging	0.93	10.4
Portugal	Developed	0.92	10.4
Canada	Developed	0.92	10.3
New Zealand	Developed	0.89	10.0
Norway	Developed	0.89	10.0
Czechia	Emerging	0.89	10.0
Luxembourg	Developed	0.88	9.9
South Africa	Emerging	0.88	9.9
India	Emerging	0.87	9.8
China	Emerging	0.86	9.7
Belgium	Developed	0.85	9.5
Greece	Developed	0.84	9.5
Netherlands	Developed	0.84	9.4

Brazil	Emerging	0.83	9.4
Poland	Emerging	0.82	9.2
Australia	Developed	0.81	9.2
Mexico	Emerging	0.80	9.0
Hungary	Emerging	0.79	8.9
Italy	Developed	0.78	8.8
Indonesia	Emerging	0.78	8.7
Switzerland	Developed	0.64	7.2
Slovenia	Emerging	0.60	6.8
Ireland	Developed	0.60	6.7
Israel	Developed	0.57	6.5
Türkiye	Emerging	0.54	6.0
Iceland	Developed	0.53	5.9

Note S1. Data construction and country classification.

Y02 patent and total patent data were obtained from the OECD Data Explorer (dataflow "Environment-related technologies patents", agency OECD.STI.PIE, version 1.0), filtering by patent authority "IP5 patent family", date type "Priority date", agent role "Inventor", and technology domain "Climate change mitigation" (equivalent to Y02) or "Total patents" as appropriate, for the period 1990–2020 and the 40 countries in the sample (source last updated April 2026). The EPS index was obtained from the OECD Data Explorer (dataflow "OECD Environmental Policy Stringency Index", agency OECD.ECO.MAD, version 1.0) at an annual frequency, for the same period and countries (last updated September 2024). Trade, GDP per capita, and population indicators were obtained from the World Bank public API (api.worldbank.org/v2) indicators NE.TRD.GNFS.ZS, NY.GDP.PCAP.KD, and SP.POP.TOTL, respectively (last updated July 2026). The three datasets were merged by ISO3 country code and year into a single panel and analyzed in R.

For the additional robustness analyses, two further World Bank indicators were used: exports and imports of goods and services, each expressed as a percentage of GDP (indicators NE.EXP.GNFS.ZS and NE.IMP.GNFS.ZS, respectively, same source and update date as above), used to decompose trade openness into its export and import components; and the government effectiveness indicator from the World Bank Worldwide Governance Indicators (indicator GOV_WGI_GE_SC, 0–100 scale, country averages over 1996–2020), used to test whether the EPS–green patenting relationship varies with institutional quality. Both were merged into the panel by ISO3 country code and year using the same procedure as the original indicators.

Country group classification: "Emerging" denotes the BRIICS bloc (Brazil, Russia, India, Indonesia, China, South Africa) plus nine OECD economies that underwent income-convergence processes for much of the sample period (Chile, Mexico, Türkiye, Poland, Hungary, the Slovak Republic, Slovenia, Czechia, and Estonia)—15 economies in total. The remaining 25 OECD countries in the sample are classified as "Developed". This classification, based on World Bank income trajectories over the study period, is documented explicitly to allow for replication or modification in future work.

All estimations reported in the main regression tables and the beta- and sigma-convergence analysis (Section 4.6) were performed in R (version 4.3.3) using the following packages: dplyr for panel data manipulation and transformation; plm (Croissant and Millo, 2008) for panel data model estimation (pooling, fixed effects, random effects) and specification tests (Hausman, F-test); sandwich and lmtest for heteroskedasticity-robust and cluster-robust standard errors; ggplot2 and patchwork for data visualization and

multi-panel figure composition; and tidyr for data reshaping in the convergence analysis. The Poisson pseudo-maximum likelihood models in Table 5 (Section 3.3) and the panel autoregressive robustness check in Section 4.6 were estimated separately in Python (version 3.13), using statsmodels (version 0.15.0) and linearmodels (version 7.0), respectively, as described in those sections. The compiled panel dataset and the complete R and Python analysis scripts are available from the corresponding author upon reasonable request.